DEEP SPACE ONE: NASA'S FIRST DEEP-SPACE TECHNOLOGY VALIDATION MISSION

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Under development for launch in July 1998, Deep Space One (DS 1) is the first flight of NASA's New Millennium Program, chartered to validate selected technologies required for future low-cost space science programs. Advanced technologies chosen for validation on DS 1 include solar electric propulsion, high-power solar concentrator arrays, autonomous on-board optical navigation, two low-mass science instrument packages, and several telecommunications and microelectronics devices. Throughout the two year primary mission, the technology payload will be exercised extensively to assess performance so that subsequent flight projects will not have to incur the cost and risk of being the first users of these new capabilities. An important component of the DS 1 mission is diagnosing any in-flight anomalies or failures. Although DS 1 is driven by the requirements of the technology validation, it also presents an important opportunity to conduct solar system science. During the primary mission, the spacecraft will fly by asteroid 3352 McAuliffe, Mars, and comet P/West-Kohoutek-Ikemura. The two science instruments that are being validated, an integrated visible imager and UV and IR imaging spectrometer and a plasma physics package, will be used to collect science data during the cruise and encounters. In addition, a suite of fields and particles sensors included to aid in the quantification of the effects of the solar electric propulsion on the spacecraft and near-space environment will be used for science measurements complementary to those of the plasma instrument. The return of science data will demonstrate that the technologies are compatible with the demands of future scientific missions and will ensure that this rare opportunity to encounter such a variety of solar system targets during a short mission will be fully exploited.

INTRODUCTION

NASA'S vision of space and Earth science in the early years of the next century comprises frequent, affordable, exciting, scientifically compelling missions. Microspacecraft, small enough to be launched on low-cost launch vehicles, with highly focused objectives, will execute many of these missions.

The New Millennium Program (NMP) is designed to accelerate the realization of these missions by developing and validating some of the key technologies they need.[1] Beginning in 1998, NMP will flight validate high risk technologies using dedicated deep-space and Earth-orbiting flights. The spacecraft flown by NMP are not intended to be fully representative of the spacecraft to be flown in future missions, but the advanced technologies they incorporate are.

Although the objective of the NMP technology validation missions is to enable future science missions, the NMP missions themselves are not science-driven. They are technology-driven, with the principal requirements coming from the needs of the advanced technologies that form the "payload." The missions will be high risk because, by their nature, they will incorporate unproven technologies that, in general, will not have functionally equivalent back-ups. Indeed, if an advanced technology does not pose a high risk, validation by NMP is not required.

Deep Space One (DS 1) is the first flight of the NMP. It is being led by JPL, with Spectrum Astro, Inc. as the partner for spacecraft development. Additional background on the New Millennium Program and the selection of technologies and mission design for DS1 are given elsewhere.[2]

DS 1 ADVANCED TECHNOLOGIES

The DS 1 project is validating 12 advanced technologies. These have been selected on the basis of how relevant they are to NASA's future space science programs, how revolutionary they are, and how much the risk of their subsequent use is reduced by validating them in spaceflight. In addition, more practical issues such as schedule and compatibility with the basic DS 1 mission profile contributed to their selection.

The DS 1 advanced technology experiments are listed in Table 1. Overviews of the technologies are given in the next section in the order in which they appear in the table.

Advanced Technology
Solar electric propulsion
Solar concentrator array
Autonomous optical navigation
Integrated camera and imaging spectrometer
Integrated ion and electron spectrometer
Small deep-space transponder
K.-band solid state power amplifier
Beacon monitor operations
Autonomous remote agent
Low power electronics
Power activation and switching module
Multifunctional structure

Table 1. DS 1 Advanced Technologies.

NASA requires that DS 1 validate the first four technologies, with the rest being designated mission goals. To reach the asteroid, Mars, and comet, those required technologies and the small deep-space transponder must function. Of course, the primary objective of the project is to validate technologies, and most of the technologies on DS1 will be nearly or completely validated during the first few months of flight, well before any of the encounters. Some of the other technologies provide enhancements in the execution of the mission. Although science is not the primary goal of the mission, returning science data is an important part of the overall demonstration that all technologies are consistent with a mission that conducts science.

The success of DS 1 depends upon determining how well any of these technologies will work on future missions. If an advanced technology fails on DS1, even if it leads to the termination of the mission, as long as the failure can be diagnosed, the objective of validating the technology will be accomplished. If DS 1 could prove that an advanced technology is not appropriate for future missions, that is a valuable result. This information would achieve the goal of reducing the cost and risk to candidate future users of the technology. Of course, it is likely that such a determination would lead to modifications to the implementation of the technology, thus restoring its potential value to future space science missions.

TECHNOLOGY OVERVIEW

Overviews of the advanced technologies selected for DS 1 follow. The mission in which the technologies will be validated is discussed in the next section.

Solar electric propulsion

Solar electric propulsion (SEP) offers significant mass savings for future deep-space and Earth-orbiting missions with high Av requirements. The objective of the NSTAR (NASA SEP Technology Application Readiness) program[3], to validate low-power ion propulsion, fits well with NMP's goals. The joint JPL/Lewis Research Center effort, which was started in November 1992, has been building and ground testing ion propulsion hardware in parallel with fabricating flight hardware for DS1.

The NSTAR-provided ion propulsion system (IPS) uses a hollow cathode to produce electrons to collisionally ionize xenon. The Xe^+ is electrostatically accelerated through a potential of up to 1280 V and emitted from the 30-cm thruster through a molybdenum grid. A separate electron beam is emitted to produce a neutral plasma beam. The power processing unit (PPU) of the IPS can accept as much as 2.5 kW, corresponding to a peak thruster operating power of 2.3 kW and a thrust of about 90 mN. Throttling is achieved by balancing thruster and Xe feed system parameters at lower power levels, and at the lowest PPU input, 600 W, the thrust is about 20 mN. The specific impulse decreases from 3300s at peak power to about 1900 s at the minimum throttle level.

Because the purpose of flying NSTAR'S IPS is to validate it for future space science missions, a comprehensive diagnostic system is also on the spacecraft. This will aid in quantifying the interactions of the IPS with the remainder of the spacecraft, including advanced-technology science instruments, and validating models of those interactions. The diagnostic instrument suite includes a retarding potential analyzer, two Langrnuir probes, search-coil and fluxgate magnetometers, a plasma wave sensor, and two pairs of quartz-crystal microbalances and microcalorimeters. One of these pairs has a direct view of the ion beam, while the other is shadowed by spacecraft structure. Measurements will include the rate and extent of contamination around the spacecraft from the Xe^+ plume and the sputtered Mo from the grid, electric and magnetic fields, and the density and energy of electrons and ions in the vicinity of the spacecraft. In addition, the sensors will be used to complement science measurements of DS 1's ion and electron spectrometer (see below), particularly during the encounters.

Solar concentrator array

Because of the IPS, DS 1 requires a high power solar array. The Ballistic Missile Defense Organization, working with NASA's Lewis Research Center and AEC-Able Engineering, Inc., wants space validation of its Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET 11)[4], so flying SCARLET on DS 1 is mutually beneficial. A 180-W SCARLET I array, using similar technology, was included on the METEOR commercial experiment platform, which was destroyed in a failed Conestoga launch in October 1995.

SCARLET uses cylindrical silicone Fresnel lenses to concentrate sunlight onto $GaInP_2$/GaAs/Ge cells arranged in strips with an expected average efficiency of over 22%. Including the optical efficiency of the lenses, a total effective magnification of 7.14 is achieved. With relatively small panel area actually covered by solar cells, the total cost of cells is lowered and thicker cover glass becomes practical, thus reducing the susceptibility to radiation. The dual junction cells display significant quantum efficiencies from 400 nm to 850 nm.

The pair of arrays will produce 2.6 kW at 1 AU at the beginning of life. Each array comprises four panels that are folded for launch, and a single-axis gimbal ensures pointing in the more sensitive longitudinal axis. DS1 will be the first spacecraft to rely exclusively on concentrator arrays; it also is the first flight to use only multibandgap cells.

Autonomous optical navigation

Because operations are a significant cost in NASA science missions, NASA explicitly included autonomy in its guidelines to NMP. A reduction in requirements for Deep Space Network (DSN) tracking of spacecraft will come from the placement of a complete navigation capability onboard the spacecraft.[5] (Other autonomy technology experiments are discussed below.) The autonomous system to be validated on DS 1, AutoNav, will navigate the spacecraft from shortly after injection through the encounters using data already resident on the spacecraft or acquired and processed onboard. Stored in AutoNav will be the trajectory generated and optimized on the ground; the ephemerides of the DS 1 target bodies, about 250 distant "beacon" asteroids, and all planets except Pluto; and a catalog of the positions of 250,000 stars (all contained in the Tycho catalog).

Throughout the mission, one to two times per week, AutoNav will be invoked by the operating sequence to command the attitude control system to turn the spacecraft to point sequentially at 4 to 20 beacons. Visible-channel images from the integrated camera and imaging spectrometer (see below), each with one beacon asteroid and known background stars, are acquired. On-board image processing allows accurate extraction of the apparent position of each asteroids with respect to the stars, thus allowing the spacecraft location to be estimated. The heliocentric orbit is computed with a sequence of these position determinations combined with estimated solar pressure, calculated gravitational perturbations, and on-board knowledge of the thrust history of the IPS and incidental accelerations from unbalanced turns by the reaction control system. The trajectory then is propagated to the next encounter target, and course changes are generated by the maneuver design element. In general, those course changes will be implemented through changes in the IPS thrust direction and duration, but in certain cases described below, the maneuvers may be accomplished with the small chemical propulsion system.

Integrated camera and imaging spectrometer

Low-mass science instruments clearly are critical for future space science missions. One of the advanced technologies DS 1 will validate is the Miniature Integrated Camera-Spectrometer (MICAS), conceived and developed by a team from the United States Geological Survey, SSG, Inc., the University of Arizona, and JPL. In one 12-kg package, this derivative of the original concept for a Pluto Integrated Camera Spectrometer includes two visible imaging channels, an ultraviolet imaging spectrometer, and an infrared imaging spectrometer plus al l the thermal and electronic control. All sensors share a single 10-cm-diameter telescope. With a structure of highly stable SiC, no moving parts are required. Spacecraft pointing directs individual detectors at the desired targets.

The instrument includes two visible detectors, both operating between 500 and 1000 nm: a 1024 x 1024 CCD with 13 μrad pixels and a 256 x 25618 μrad per pixel CMOS active pixel sensor, which includes the timing and control electronics on the chip with the detector. The two imaging spectrometers operate in push-broom mode. The UV spectrometer spans 80 to 185 nm with 2.1 nm spectral resolution and 316 μrad pixels. The IR spectrometer covers the range from 1200 to 2400 nm with spectral resolution of 12 nm and 53 μrad pixels.

MICAS will serve three functions on DS 1. First, as with all the advanced technologies, tests of its performance will establish its applicability to future space science missions. Second, the visible CCD channel will be used to gather images for the AutoNav's use. Third, it will collect valuable science data during this mission at the asteroid, Mars, and comet.

Integrated ion and electron spectrometer

Just as MICAS integrates several different measurement capabilities into one low-mass package, the Plasma Experiment for Planetary Exploration (PEPE)[7] combines multiple instruments into one compact 6-kg package. Built by Southwest Research Institute and Los Alamos National Laboratory, PEPE determines the three-dimensional plasma distribution over its 2.8π sr field of view. The instrument includes a very low power, low mass microcalorimeter, provided by Stanford University, to help understand the plasma/surface interactions

PEPE measures the energy spectrum of electrons and ions from 3 eV/q to 30 keV/q with a resolution of at least 5%. instead of using moving parts, it electrostatically sweeps its field of view, achieving angular resolution of 45° in its azimuth and 5° in elevation. PEPE also measures ion mass in the range of 1 to 135 amu perunit charge with a resolution of 5%.

PEPE will serve three functions on DS 1. It will validate the design for a suite of plasma physics instruments in one package; it will assist in determining the effects of the IPS on spacecraft surfaces and instruments and on the space environment, including interactions with the solar wind; and it will make scientifically interesting measurements during the cruise and the encounter with the comet and Mars (and possibly the asteroid). Indeed, a key investigation of DS1 will be whether space physics measurements can be made from a spacecraft operating with an ion propulsion system to assure future users that there are no incompatibilities. The high mass resolution of PEPE enables it easily to distinguish between the two major species emitted by the IPS, Xe and Mo.

Telecommunications technologies

DS 1 will validate a small deep-space transponder (SDST), built by Motorola, and a K_a-band solid state power amplifier developed by Lockheed Martin. Combining the receiver, command detector, telemetry modulation, exciters, beacon tone generation (see below), and control functions into one package of about 3.2 kg, the SDST allows X-band uplink and X-band and K_a-band downlink. The K,-band signal is amplified by the 0.6 kg power amplifier, which generates 2.6 W output with an overall efficiency of 13% -15%. The SDST supports both uplink and downlink radio science modes of operation, and it provides coherent and noncoherent operation for radio navigation purposes (in addition to basic communications). To achieve the SDST'S functionality without a new technology development would require over twice the mass. This compact, low-mass transponder is enabled by the use of advanced GaAs monolithic microwave integrated circuits, high density packaging techniques, and silicon ASICs. Such telecommunications advances for future missions are described in more detail elsewhere.[8]

Beacon monitor operations

The SDST generates the four tones needed for beacon monitor operations conceived to reduce the large demand that would be expected on the DSN if many missions were in flight simultaneously, as envisioned by NASA. In beacon monitor operations, an on-board data summarization system determines the overall spacecraft health and selects one of four tones to transmit to indicate to the ground operations team what action, if any, is necessary. Without data modulation, these tones are easily detected with small, low-cost systems on Earth, reserving the more expensive large DS N stations for command radiation and data reception when the beacon indicates that such services are needed. The four tones correspond to the spacecraft not needing any assistance because all is well; informing the ground that there was a problem that the spacecraft resolved; alerting the ground that the spacecraft has data that are ready to be transmitted, so a DSN pass should be scheduled; and requesting assistance because the spacecraft has encountered a problem it was unable to solve. Experiments to be conducted during the mission include not only the data summarization and tone generation and detection, but also DSN responses. Beacon monitor operations may be used during DS 1 to aid in ensuring that the IPS is operating between scheduled DSN communication sessions.

Autonomous remote agent

The autonomous operations capability DS 1 will validate represents an entire architectural approach that is expected to be applicable to a wide range of future science missions.[10] The team developing this system is drawn from JPL, Ames Research Center, and elsewhere. Rather than standard remote control, this approach uses an agent of the ground team onboard the spacecraft. This remote agent will be tested in a restricted case on DS 1, in preparation for more ambitious experiments on subsequent flights. The remote agent includes an on-board mission manager that carries the mission plan, expressed as high-level goals. A planning and scheduling engine uses the goals, comprehensive knowledge of the spacecraft state, and constraints on spacecraft operations to generate a set of time-based or event-based activities, known as tokens, that are delivered to the executive. The executive expands the tokens to a sequence of commands that are issued directly to the appropriate destinations on the spacecraft. The executive monitors the response to these commands and reissues or modifies them if the response is not what was anticipated.

The design is flexible enough to handle a variety of unexpected situations onboard, and its access to a much more complete description of the spacecraft state than would be available to ground controllers in a traditional operations concept allows it to make better use of on-board resources. A mode identification and reconfiguration engine allows recovery or work-arounds in the presence of faults without requiring help from the ground except in extraordinary cases. Several faults will be simulated during the remote agent experiment on DS 1.

Microelectronics and structures

Electronics mass, volume, and power consumption are important drivers for overall spacecraft design. DS 1 includes tests of two microelectronics technologies and an mechanical/electronic experiment intended to contribute to the achievement of NASA's vision of spacecraft in the future. To reduce the power consumption of electronics, one experiment uses devices with very low voltage and low capacitance.[11] This low-power electronics experiment contains a ring oscillator, multipliers, and discrete transistors to test 0.9-volt logic and 0.25-pm gate lengths (achieved with 248-rim lithography). Provided by the Massachusetts Institute of Technology Lincoln Laboratory, this experiment will validate the performance of these devices throughout the life of the mission, with particular interest in the effects of radiation. DS 1 also will test a power activation and switching module[12], the result of a joint development among Lockheed Martin, Boeing, and JPL. This device contains two sets of four power switches, each set controlled by its own mixed signal ASIC, providing current limiting and current and voltage sensing. High-density packaging technology quadruples the packing density over the current state of the art. Designed to be capable of switching up to 40 V and 3A, the PASM as an experiment will switch an internal test load on DS 1.

A multifunctional structure[13], provided by the United States Air Force Philips Laboratory and Lockheed Martin Astronautics, is incorporated as an experiment. This new packaging technology combines load-bearing elements with electronic housings and thermal control, thus greatly reducing the mass of spacecraft cabling and traditional chassis. The DS 1 experiment will return data on the performance of the electronic connection systems for embedded test devices and the thermal control for a test panel incorporating such a multi functional structure.

MISSION

NASA directed that DS 1 encounter one asteroid and one comet during its primary mission. It was decided early in NMP that a complete validation of the technologies would require flying them on missions that bore strong resemblance to science missions of the future. DS 1's mission was focused on small bodies because of the great interest in exploring them in future missions, the ease in reaching some for this validation flight, and the desire to conduct a mission that NASA's principal customer (the United States taxpayers) would find exciting.

Another constraint on the mission derives from the need to return results promptly to the future users. Except for tests of lifetime, most technologies could be evaluated on short missions as well as long ones, so it was decided that the primary mission should last no longer than about two years. This would allow sufficient time to conduct an exciting mission and to exercise the technologies under a wide range of conditions without forcing eager potential users to wait unreasonably long before being confident about their use. NASA has strongly supported a high risk mission for DS 1 (and the other NMP missions), and it has encouraged the project to develop plans for a particularly bold and exciting extended mission.

DS 1's launch period extends from July 1 to July 31, 1998, with the opening dictated principally by spacecraft readiness. It will launch on the first McDonnell Douglas Aerospace Delta 7326-9.5, the smallest vehicle in the Delta stable, and will be the first launch of NASA's Med-Lite program. This launch vehicle was selected largely on the basis of prompt availability and low cost, but its capability exceeds what is needed for DS 1, with relatively low mass and low injection energy (in part attributable to the high performance of the IPS). The residual launch vehicle performance has allowed the manifesting of another spacecraft on this launch. SEDSAT- 1, built by the Students for the Exploration and Development of Space at the University of Alabama in Huntsville, in collaboration with NASA's Marshall Space Flight Center and Johnson Space Center, will be mounted on the second stage, which accomplishes insertion into Earth orbit. After the second stage's second bum, to raise the orbit of the third stage and DS 1, the stage separates and carries SEDSAT-1 to its intended orbit, where it is separated. The third stage completes DS 1's injection to heliocentric orbit.

An overview of the trajectory for launch at the beginning of the launch period is shown in Figure 1. *Some* details will change by a few days, depending upon the final performance realized for the IPS and SCARLET (and when during the launch period the launch occurs). After injection, two weeks will be spent performing initial evaluation of the spacecraft, with focus on basic spacecraft health as well as those functions needed for the long duration IPS thrusting. The solar arrays, transponder, IPS, AutoNav, and MICAS visible channel are the technologies that will receive the early attention. Ground-based determination of the actual trajectory after injection will be combined with results of the first SCARLET and IPS tests to generate and optimize an updated low-thrust trajectory that will be transmitted to the spacecraft. Thereafter, the baseline plan is for all navigation to be accomplished exclusively by the on-board autonomous navigation system. Conventional radio navigation will be used to validate the performance of AutoNav.

Fifteen days after launch (L+15), the IPS will begin an 11-day thrust period. With the spacecraft in constant communications with the DSN, this will provide the first opportunity to gain experience with the IPS for deterministic thrust. A 5-day gap in thrusting from L+26 to L+30 is designed to allow time to activate PEPE (after spacecraft outgassing has reached acceptable levels), deploy the protective, UV-opaque cover on MICAS, and recover from anomalies.

The mission and trajectory designs account for regular suspensions in IPS thrusting. One to two times per week (and more frequently prior to encounters) the spacecraft will turn to collect its optical navigation images. During times of IPS thrusting, this will require the spacecraft to turn away from the thrust vector. The IPS thruster gimbal allows pointing of the thrust vector through the spacecraft center of mass, but the spacecraft attitude during IPS thrust is fixed by the need to achieve thrust in a particular direction and to keep the solar arrays normal to incident sunlight for maximum power. In addition, some DSN passes will use the body-fixed X-band high gain antenna, requiring the spacecraft to point it at Earth. To maintain as high an IPS thrusting duty cycle as possible, DSN contact will be accomplished through one of the three low gain antennas whenever the lower antenna gain is sufficient. Besides the predictable hiatuses in IPS thrust, anomalies that prevent thrusting are accounted for by designing for a lower duty cycle.

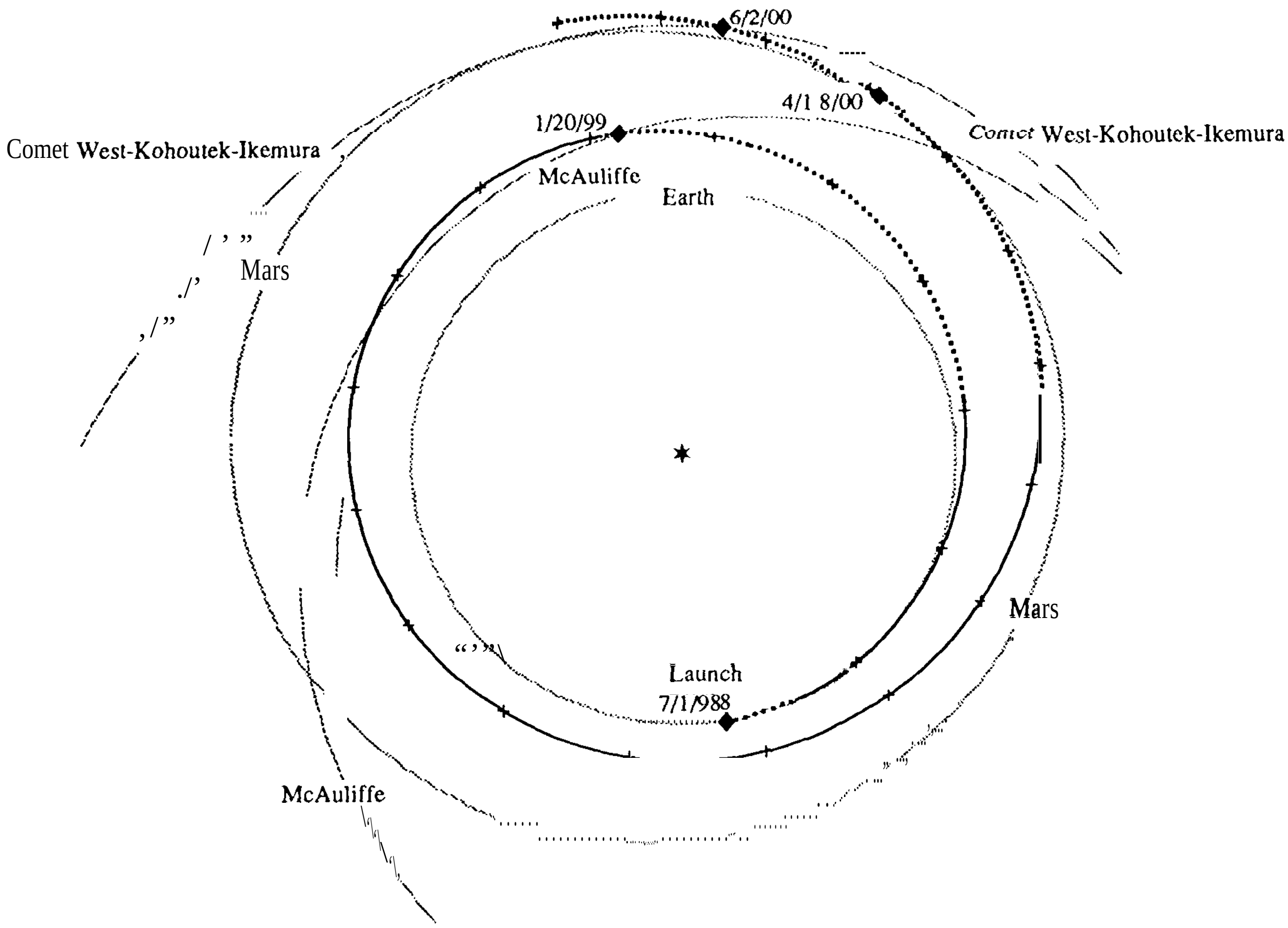


Figure 1. DS1 trajectory. The solid line indicates the IPS thrust is on; the dotted portion is for ballistic coast. The tic marks are at 30-day intervals,

During most of the mission, one 8-hour DSN pass each week will allow commanding and return of spacecraft health and technology validation data. Because of the importance of maintaining IPS thrust, at least one shorter pass is scheduled between the longer ones. Conducted only with one of the low-gain antennas to allow communication during thrusting, this pass will reveal whether the IPS is thrusting as expected and provide an opportunity to begin recovering from anomalies with minimal loss of thrust time.

Sequences will operate for 4 weeks during most of the mission. The small ground team makes extensive use of existing tools and services JPL has developed to support a wide range of missions. With these and standards such as CCSDS (Consultative Committee for Space Data Standards), the ground segment's cost is kept to a minimum.

Throughout the cruise, most of the technologies will be exercised. Some simply will require regular activation and checks of their health. Others, such as the solar arrays and telecommunications technologies, will require spacecraft maneuvers to evaluate their performance under different Sun or Earth viewing angles and thermal conditions. Certain times are devoted to specific validation activities that affect other subsystems, such as the remote agent experiment, which will control other parts of the spacecraft during its tests. Many of the technologies will be used as part of the execution of the basic mission.

On January 19, 1999, the spacecraft will encounter 3352 McAuliffe at 7.8 km/s. This S-type Earth-approaching asteroid is estimated to be 1 km in radius. During the final 20 days of the spacecraft's approach to the body, AutoNav will require optical navigation images and trajectory correction maneuvers at an increasing frequency to control the targeting of the final encounter. These small maneuvers may be conducted with the IPS or the hydrazine reaction control system (RCS). The RCS will be used for the maneuvers during the final day to save time; it may be used in earlier maneuvers if the calculated r-maneuver duration exceeds the time allocated for the IPS. The decision will be made onboard. In addition, if thrust is required in an attitude that is disallowed by the attitude control system, it will be decomposed into two allowed maneuvers without ground intervention.

Because the size and shape of McAuliffe are not well known, a flyby altitude of 10 km is planned, With an expected navigational delivery accuracy of better than 3 km, this assures a safe but very exciting encounter. The last opportunity for a trajectory correction maneuver will be 3 hours before closest approach. If previously enabled by ground command, AutoNav, based on its analysis of the approach images, will make a determination if a closer encounter is safe. If it is, a "bold maneuver" will be executed autonomously to reduce the closest approach altitude to 5 km. During the final approach, AutoNav's MICAS images will be interspersed with MICAS images and spectra collected for science purposes. The late navigation images will contain information AutoNav needs to provide rapid updates to its estimates of the range to McAuliffe, critical for keeping the asteroid in MICAS' field of view. Because MICAS is body-fixed, the surface resolution achieved will be limited by when the angular rate of the body exceeds the attitude control system's capability to keep McAuliffe in the MICAS boresight. The highest surface resolution for visible images is expected to be in the range of 1 m to 5 m per pixel.

The asteroid encounter will allow an opportunity to gather science data on the size, shape, spin state, geomorphology, albedo, and the mineralogy of the surface material and its compositional heterogeneity. It also may be possible to measure or, at least constrain, the magnetization and the interaction of the body with the solar wind, including sputtering. The final science plans for the encounter will be developed in early 1998.

The deterministic thrust resumes 4 days after the closest approach, by which time essentially all science and technology validation data from the encounter will have been returned. This thrust arc lasts for approximately 340 days. By the end of the thrusting, the spacecraft will have expended about 75 kg of Xe (for deterministic thrust as well as navigational needs, specific IPS validation experiments, and two-axes of attitude control), providing a total velocity change of about 3.6 km/s.

In April 2000, DS 1 encounters Mars for a modest gravity assist. This event provides a bonus opportunity to conduct additional technology validation and science data acquisition with MICAS, PEPE, AutoNav, and the IPS diagnostics sensors at Mars. The flyby speed is *3.4* km/s. The altitude may be adjusted to improve mission performance, but the baseline is 10,000 km from the planet's center. Depending upon mission resources, an encounter with Phobos or Deimos is possible.

In June 2000, DS 1 reaches comet 76P/West-Kohoutek-Ikemura, a few weeks after the comet's perihelion. AutoNav will use images initially of the coma and finally of the nucleus to calculate corrections to the trajectory for a close flyby. With an encounter speed of 14 km/s, science data at the comet that may be collected include the structure and composition of the coma and tail (including gas, plasma, and dust), the nature of jets and their connection to sufrace features, the interaction with the solar wind, and the same kind of characterization of the nucleus as at the asteroid. The cometary environment is highly uncertain, as is the response of the spacecraft to debris. The current baseline is for a 500-km flyby, although substantial work on the final encounter plans remains.

The primary mission ends with the completion of the return of data from the comet encounter. Solar conjunction in late June 2000 will interrupt the data transmission for about two weeks but may afford an opportunity for radio science.

If the spacecraft is healthy and project resources permit, an extended mission will be attempted. Subsequent encounter targets will be investigated; test cases have suggested that an additional asteroid encounter may be possible, and comet encounters and a return to the Earth/moon system will be considered. All of these options will depend upon the trajectory during the primary mission; with the new technology IPS, SCARLET, and AutoNav, and their corresponding performance uncertainties, detailed extended-mission planning must await more information from the primary mission. During the extended mission, extremely stressing tests may be conducted of the advanced technologies that are not reasonable during the primary mission. The operation of the spacecraft may be turned over to students.

SPACECRAFT

Clearly there are not enough advanced technologies on DS 1 to compose an entire spacecraft. Because the focus of NMP is on the validation of these technologies for future missions, not on building complete spacecraft representative of those to be used in future science missions, the remainder of the spacecraft utilizes existing low-cost components. As part of the agreement with NASA that this will be a high-risk, low-cost mission, the spacecraft is principally single string with Class B parts. The design includes limited internal redundancy in some devices, and some functional redundancy at the subsystem level. Wherever possible, standard interfaces are used. The spacecraft design is driven by the needs of the advanced technologies and the technology-driven mission design.

The spacecraft structure is an aluminum space frame based on the three Miniature Seeker Technology Integration (MSTI) spacecraft built by Spectrum Astro, Inc. for BMDO. With most of the components mounted on the exterior of the bus, their accessibility simplifies replacement during integration and test. Because the spacecraft diameter is small, a boom is included to aid in reaching the hydrazine and xenon lines when the spacecraft is in the launch vehicle payload fairing. Thermal control is accomplished with standard multilayer insulation, heaters, and radiators.

Attitude control sensors include a stellar reference unit and inertial measurement unit for normal operations, and a sun sensor for use in contingencies. A hydrazine reaction control system provides three-axis stabilization (when the IPS is not thrusting) and can be used for small course changes as described above. During IPS thrusting, the IPS thruster is gimbaled to control two axes, with the RCS providing control around the thrust axis.

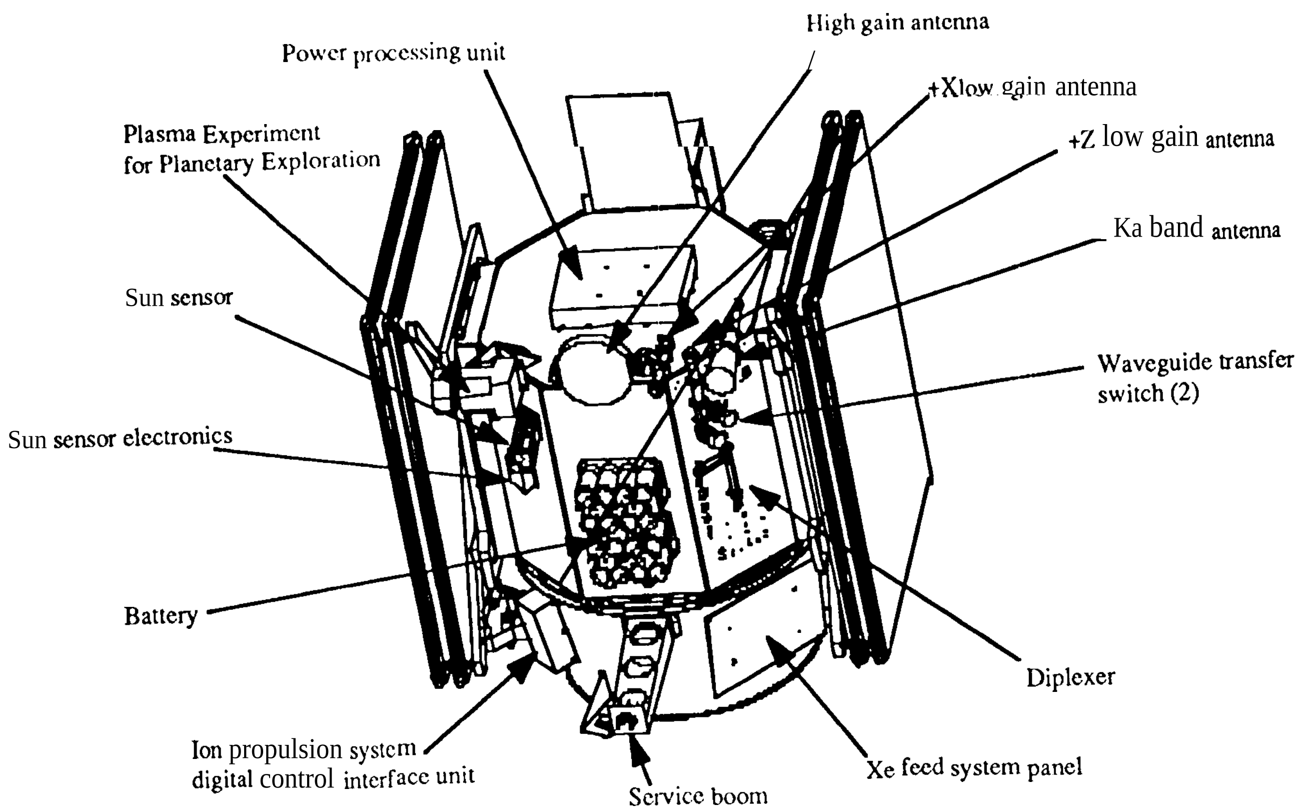
Most of the electronics are enclosed in the integrated electronics module with a VME backplane, and most remote devices communicate over a 1553 bus.

The IPS PPU requires high voltage for its operation. The output from the solar arrays is 100 V, and this power is fed directly to the PPU; a converter provides regulated 33 V to the spacecraft bus. A 24 A-hr NiH_2 battery, provided by the U. S. Air Force/Phillips Laboratory, provides energy between launch and first light on the solar arrays and supplements the solar array power during IPS thrusting to cover transients in the spacecraft's power consumption. The battery also will be used if encounter geometry requires that the arrays be too far off-Sun for them to power the spacecraft.

The total injected mass is about 475 kg, comprising the 375 kg spacecraft, 25 kg of hydrazine, and 75 kg of Xe. The spacecraft configuration is shown in Figure 2.

CONCLUSION

The flight of DS1 will provide extensive data useful for the validation of technologies important for NASA's vision of space and Earth science missions of the future. Indeed, important progress on these technologies has already been made because of the work necessary to incorporate them into a space mission. This impetus has provided the technology teams valuable insight into implementation issues that would not be expected to arise in typical technology development or conceptual mission studies. In addition, spacecraft, mission, and


High gain antenna
Power processing unit
+X low gain antenna
+Z low gain antenna
Plasma Experiment
for Planetary Exploration
Ka band antenna
Sun sensor
Waveguide transfer
switch (2)
Sun sensor electronics
Battery
Diplexer
Ion propulsion system
digital control interface unit
Service boom
Xe feed system panel

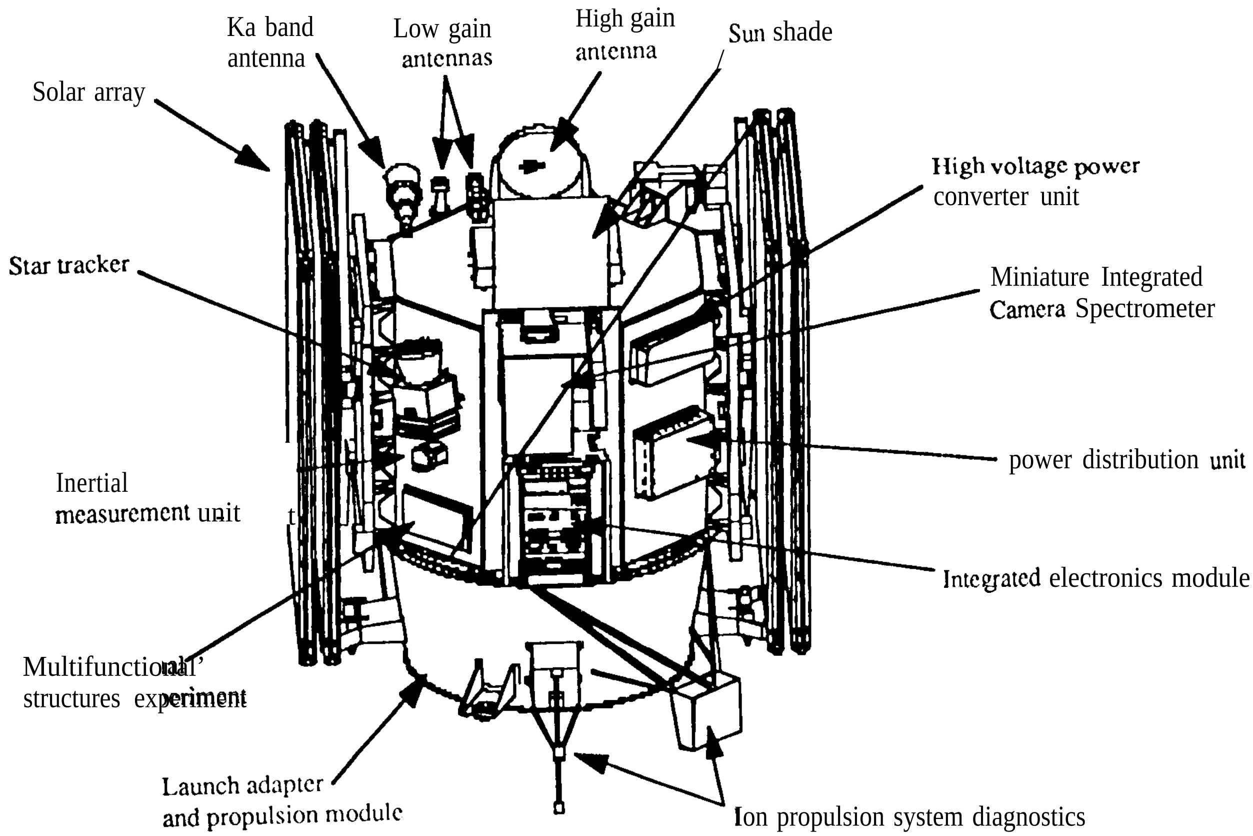

Ka band
antenna
Low gain
antennas
High gain
antenna
Sun shade
Solar array
High voltage power
converter unit
Star tracker
Miniature Integrated
Camera Spectrometer
power distribution unit
Inertial
measurement unit
Integrated electronics module
Multifunctional
structures experiment
Launch adapter
and propulsion module
Ion propulsion system diagnostics

Figure 2. DS1 configuration. When the solar arrays are deployed, they span 11.5 m.

ground engineering teams have begun learning the implications of incorporating these valuable new technologies into their designs (and, of course, taking advantage of the capabilities of the technologies in creating new designs). Thus, some of the benefits of the rapid infusion of these new technologies into spaceflight have already been realized; and any informed user, seeking to take advantage of the capabilities of these advanced technologies, now would encounter lower risk and cost by building upon the results of DS 1's work to date. The actual execution of the mission is expected to provide many more lessons of value for future spaceflight projects.

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REFERENCES

1. Casani, E. Kane, "The New Millennium Program: An Overview," Space Technology and Applications International Forum 1997, Albuquerque, NM, January 26-30, 1997.

2. Rayman, Marc D. and David H. Lehman, "NASA's First New Millennium Deep-Space Technology Validation Flight," Second IAA International Conference on Low-Cost Planetary Missions, Laurel, MD, April 16-19, 1996, IAA-L-0502.

3. Stocky, John F., Robert Vondra, Alan M. Sutton, "U.S. In-Space Electric Propulsion Experiments," AGARD Flight Vehicle Integration Panel Symposium, Cannes, France, October 3-6, 1994.

4. Murphy, David M. and Douglas M. Allen, "SCARLET Development, Fabrication, and Testing for the Deep Space 1 Spacecraft," *Proceedings of the Intersociety Energy Conversion Engineering Conference,* Honolulu, HI, July 28-August 1, 1997, paper 97539.

5. Riedel, J. E., S. Bhaskaran, S. P. Synott, S. D. Desai, W. E. Bellman, P. J. Dumont, C. A. Halsell, D. Han, B. M. Kennedy, G. W. Null, W. M. Own Jr., R. W. Werner, and B. G. Williams, "Navigation for the New Millennium: Autonomous Navigation for Deep Space 1," 12th International Symposium on Space Flight Dynamics, Darmstadt, Germany, 2-6 June 1997, paper 88.

6. Beauchamp, P. M., R. H. Brown, C. F. Bruce, G-S. Chen, M. P. Chrisp, G. A. Fraschetti, T. N. Krabach, S. W. Petrick, D. H. Rodgers, J. Rodriguez, S. L. Soil, A. H. Vaughan, L. A. Soderblom, B. R. Sandel, and R. V. Yelle, "Pluto Integrated Camera Spectrometer (PICS) Instrument," *Acta Astronautica 35,* Supplement 1995.

7. Bolton, S. J., D. T. Young, J. L. Burch, N. Eaker, J. E. Nordholt, H. O. Funsten, and D. J. McComas, "Plasma Experiment for Planetary Exploration (PEPE)," Space Technology and Applications International Forum 1997, January 26-30, 1997, Albuquerque, NM.

8. Rafferty, W., D. Rascoe, G. Fujikawa, and K. Perko, "Small Spacecraft Telecommunications for the New Millennium's Technology Validation Missions," AIAA 34th Aerospace Science Meetings, Reno NV, January 15-18, 1996, AIM 96-0700.

9. Wyatt, E. J., M. Foster, A. Schlutsmeyer, R. Sherwood, M. Sue (1997) "An Overview of the Beacon Monitor Operations Technology," International Symposium on AI, Robotics, and Automation in Space, Tokyo, Japan, July 14-16, 1997.

10. Bernard, Douglas E. and Barney Pen, "Designed for Autonomy: Remote Agent for the New Millennium Program," International Symposium on AI, Robotics, and Automation in Space, Tokyo, Japan, July 14-16, 1997.

11. Keast, C. L., R. Berger, J. A. Burns, J. M. Knecht, R. R. Kunz, H. I. Liu, A. M. Soares, D. C. Shaver, P. W. Wyatt, "A Sub-0.25μm Fully Depleted SOI CMOS Process for Low Power

High Performance Applications," *1997 Digest of Papers, Government Microcircuit Application Conference,* pp. *333-336.*

12. Carr, Gregory A. and Lauro A. France, "X2000 Power System Architecture," *Proceedings of the Intersociety Energy Conversion Engineering Conference,* Honolulu, HI, July 28-August 1, paper 97227.

13. Sercel, Joel, Brantley Hanks, William Boynton, Costa Cassapakis, Edward Crawley, Michael Curcio, Alok Das, William Hayden, David King, Lee Peterson, Suraj Rawal, Thomas Reddy, and Joseph Sovie, "Modular and Multifunctional Systems (MAMS) in the New Millennium Program," AIAA 34th Aerospace Science Meetings, Reno NV, January 15-18, 1996, AIAA 96-0702.